# TWA Simulator: a Graphical User Interface for T-wave Alternans

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## Abstract

*T-wave alternans (TWA) is an every-other-beat fluctuation of the T-wave amplitude, often at microvolt (invisible) levels. It is recognized as an important risk index of severe ventricular arrhythmias, leading sometimes to sudden cardiac arrest. Many algorithms for automatic detection and quantification of TWA have been proposed; when applied to the same electrocardiogram (ECG), they may provide a different TWA quantification, making interpretation of differences difficult. Aim of this work is to propose TWA Simulator as a useful tool to validate and compare TWA identification methods. TWA Simulator is a user-friendly MATLAB graphical user interface (GUI) able to generate, model, visualize and store simulated ECG (SECG) affected by TWA of known morphology and amplitude. SECG is constructed by a N-fold repetition of a template, constituted by a real and clean ECG beat. Both number of beats and RR inter-beat variability can be set by the user. Both direct and inverted TWA can be simulated. Direct TWA is simulated by adding a waveform (among four possibility) to every other T wave; inverted TWA is simulated by changing T-wave polarity in every-other SECG beat. Availability of TWA Simulator would allow efficient validation and comparison of automatic TWA identification methods by helping interpretation of results.*

## 1. Introduction

T-wave alternans (TWA) is a phenomenon defined as an every-other-beat fluctuation in the morphology and amplitude of the T-wave on the electrocardiogram (ECG). The physiological meaning of this phenomenon resides in the beat-to-beat alternation of action potential duration at the level of cardiac myocytes, thus reflecting a spatio-temporal heterogeneity of repolarization [1]. Research interest on this ECG trait has been driven by clinical and experimental evidence of TWA relationship with many cardiac pathologies such as long QT syndrome [2,3] and acute myocardial infarction [4,5], determining susceptibility to malignant ventricular arrhythmias and sudden cardiac death (SCD) [6,7]. Although some rare cases of macroscopic TWA could be found [8], such T-waves morphology/amplitude fluctuations are generally at microvolt (thus microscopic) levels, thus requiring automatic techniques to be identified.

Several algorithms aiming to automatically detect and quantify TWA have been proposed [1,5,7,9-11]. When applied to the same ECG, these techniques may provide a different TWA quantification, due to different hypotheses on TWA profile underlining their algorithms [12-14]. Thus, although comparisons of methods have been performed in the literature [15], interpretation of differences in TWA values is not always straightforward.

Since reliability of algorithms is usually first tested on simulated ECG datasets before their application to real ECG data, aim of this work is to propose TWA Simulator as a useful tool to validate and compare TWA identification methods, by providing the possibility to generate simulated ECG signals affected by TWA with controlled features.

## 2. TWA Simulator

TWA Simulator was designed as a graphical user interface (GUI) and provides an easy-to-use tool for generating, modelling, visualizing and storing simulated ECG (SECG) affected by TWA of known morphology and amplitude. TWA Simulator was developed according to the object-oriented programming (OOP) paradigm under MATLAB® environment (release R2017b).

Each SECG is constructed by a N-fold repetition of a template, constituted by a real and clean ECG beat. After having started TWA Simulator, a dialog window is shown to set some mandatory simulation parameters ("Simulation options", Fig. 1). After setting simulation parameters, TWA Simulator displays a window including three panels (Fig. 2): namely, the "T-wave" panel, which allows the setting of TWA parameters; the "Sim ECG" panel, which allows the visualization of the resulting SECG affected by the desired TWA and the "Options" panel, which includes functionality for the storage of SECG signals.

## 2.1. "Simulation options" panel

The "Simulation options" panel (Fig. 1) allows the user to set two basic information about the SECG signal: namely, the number of beats (N) and the RR (i.e. the temporal distance between two consecutive R-peaks) inter-beat variability. The "Number of beats" option can be set through an edit box and determines the amount of ECG-beat template repetition. By default, the number of simulated beats cannot be less than four.

Distribution of the inter-beat intervals was modelled as a Gaussian random variable with mean $\mu_{RR}$ and standard deviation $\sigma_{RR}$. The mean inter-beat interval $\mu_{RR}$ (i.e. the heart period of the ECG template) was fixed to 750 ms while $\sigma_{RR}$ can be manually set as a percentage of $\mu_{RR}$ by using an increment/decrement button. This means that the user can keep a constant heart rate setting a RR variability value of 0% (default option) as well as vary it up to the 10% (with a sensibility of 1% per step) which is usually reputed to be a limit for RR variability.

## 2.2. "T-wave" panel

The "T-wave" panel (red box in Fig. 2) allows the user to set the characteristics of TWA to be simulated. Both direct and inverted TWA can be simulated. Direct TWA is simulated by adding a waveform s(t) to every other T wave; user may choose among four different TWA profiles (rectangular, triangular, gaussian and brownian), and has to set TWA amplitude as well as onset and offset (both within J point and T offset) of the alternating SECG segment. Inverted TWA (macroscopic) is simulated by changing T-wave polarity in every-other SECG beat.

For the simulation of direct TWA, TWA Simulator requires to set the following parameters:

- *Waveform*: a pop-up menu allows the selection of s(t) signal waveform among four options: rectangular, triangular, gaussian or brownian.
- *Start and End*: two edit boxes allow to set the start ($t_i$) and end time ($t_f$) of the s(t) signal. Start and end time are expressed in terms of percentage of T-wave duration. By default, start and end time of the s(t) signal are set to the start (J point) and end time ($T_{offset}$) of the ECG template T wave.
- *Amplitude*: an edit box allows to express the amplitude (A) of the s(t) signal (in $\mu$V), interpreted as the maximal excess voltage of alternating T-waves over the straight ones.

If the "rectangular" or "triangular" option is selected in the *Waveform* menu, s(t) is modelled as a standard rectangular or triangular pulse, respectively.
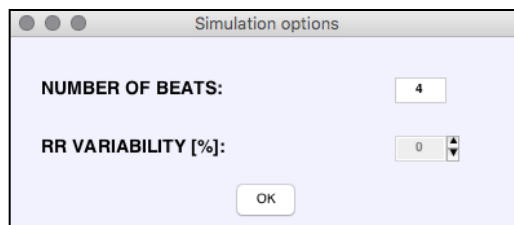


Figure 1. "Simulation options" panel.

If the "gaussian" option is selected, s(t) signal waveform is generated according to the following expression:

$$s(t) = A \cdot e^{-\frac{1}{2}\left(\frac{6(t-t_c)}{t_f-t_i}\right)^2} \qquad (1)$$

where A is the amplitude set in the *Amplitude* edit box; $t_i$ and $t_f$ are the start and end time set in the *Start* and *End* edit boxes, respectively and $t_c$ is the middle point of the [$t_i$, $t_f$] interval. The equation (1) has been tailored on the request of a Gaussian waveform with the 90% of its area concentrated in the $t_f$-$t_i$ interval.

If the "brownian" option is selected, s(t) is a realization of a Wiener process in which the independent increment at each step is generated according to the following expression:

$$W_{t+u} - W_t = \left(\frac{logA}{100}\right) \cdot X \qquad (2)$$

with $W_0 = 10^{-2} \cdot logA$. X describes a white noise process.

Simulation of the inverted TWA can be performed by selecting the "Inverted" check box and, in this case, TWA Simulator will not require further information. Error dialog boxes provide warnings to the user about possible discordances in the parameters definition. Examples of possible T-wave morphologies are shown in Fig. 3.

After defining the typology of TWA to be simulated and eventually, the characteristics of the s(t) signal, the "Start" button allows generation of the SECG(t) signal. SECG(t) signal is generated according to the following steps:

1. in the case of microscopic TWA, s(t) is alternately superimposed to the ECG template; thus, for one beat SECG(t) = ECG$_{TEMP}$(t) whereas for the successive beat SECG(t) = ECG$_{TEMP}$(t) + s(t); in the case of macroscopic TWA, SECG(t) is generated by inverting T-wave polarity in every-other beat;
2. SECG(t) is warped (stretched or compressed) according to the new heart period, randomly generated as a Gaussian random variable according to the specification given in the "Simulation option" panel;
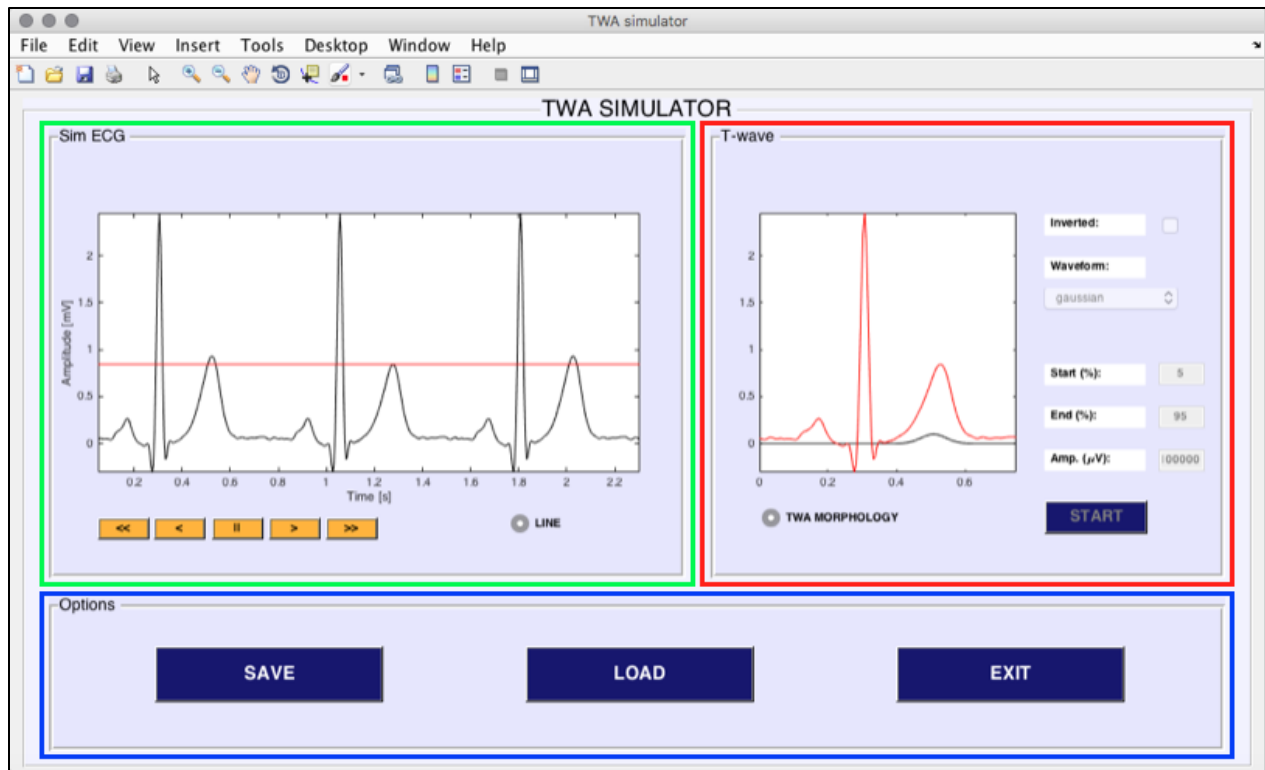3. the generated beat of the SECG(t) signal is concatenated to the ones generated by the previous iterations.

Figure 2. TWA Simulator. Red, green and blue boxes are "T-wave", "SimECG" and "Options" panel, respectively.

The "TWA MORPHOLOGY" radio button allows the user to inspect, in the scope window of this panel, the exact morphology of the chosen s(t) signal over a single heart beat (constituted by the ECG template). After setting the T-wave parameters, the "START" button allows generation of the SECG(t) signal and displays it on the "SimECG" panel.

## 2.3. "SimECG" panel

The "SimECG" panel (green box in Fig. 2) is the display object of TWA Simulator, containing the scope where the SECG(t) signal is dynamically represented by moving its trace along the screen. A five-element group-button controls the progressing of the signal (fast rewind, rewind, pause, forward, fast forward) and the "LINE" radio button allows to observe a horizontal reference line to visually recognize the alternating T waves. Reference line is particularly helpful to perceive also small differences.

## 2.4. "Options" panel

The "Options" panel (blue box in Fig. 2) contains three buttons: a "SAVE" button, which allows creation of a *.mat file to store a specific object; a "LOAD" button allows to recall an already saved simulation; an "EXIT" button terminates the execution of the GUI and allows to

return to the MATLAB® command window.

## 3. Discussion

This work proposes TWA Simulator as a useful tool to validate and compare TWA identification methods by generating simulated ECG signals affected by TWA with controlled features. TWA Simulator allows simulation of both macroscopic and microscopic TWA; for the latter, the user can choose among four different TWA profiles (rectangular, triangular, gaussian and brownian). Moreover, TWA Simulator implementation as a GUI, provides a smart interaction with the user.

The use of simulators is nowadays increasing: this is due to their versatility and capability to favor and fasten the validation process, giving to researchers the chance to test their prototype algorithm on "easy" signals, such the simulated ones. In the case of TWA identification algorithms, the number of simulation options of TWA Simulator guides the user through the generation of simulated ECG signals affected by TWA that best matches his/her requirements.

Future improvements of the TWA Simulator will include: multi-lead ECG traces being TWA a lead-dependent phenomenon [16] and additional options for changing fundamental TWA frequency (for example every other three or more beats).
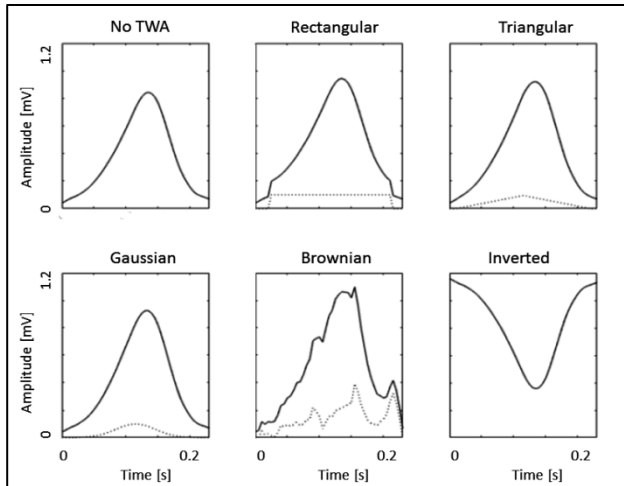
Figure 3. Different TWA profiles (dotted lines) and the related simulated T waves (continuous lines).

Eventually, analogues simulators can be developed for alternans of the other ECG waves, such as QRS complex [17], P wave [18] and U wave [19].

For research purposes, TWA Simulator can be obtained for free by contacting the research manager (Laura Burattini, l.burattini@univpm.it).

## 4.    Conclusion

In conclusion, the presented TWA Simulator is a new tool, designed as a GUI, that could be useful in validation and comparison of TWA identification methods, by helping interpretation of results.

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